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Developed in the following is the concept of heating of the chromosphere by compression waves originating in the regions of turbulence related to the convective zone of the sun. It is shown that within the chromosphere a balance can be reached between the energy resulting from the dissipation of shock waves and the energy carried off by radiation. Shock waves cause the appearance in the chromosphere of regions having differing temperatures (a two-temperature chromosphere).

It is shown that the dissipation of magnetohydrodynamic waves cannot provide a sufficient quantity of energy because of losses due to friction.

An explanation is provided for the lowering of the chromosphere above spots. The value of the density gradient in the chromosphere is discussed. An attempt is made to formulate a general idea about the chromosphere and the cause for its formation.

The entire structure of the chromosphere is determined mainly by the value of the energy flux in acoustic noises generated by the turbulence produced in the convective zone of the sun. author

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In recent years many studies have been conducted on the structure of the chromosphere and the possible causes for its heating. Many of these supplement and develop one another to a certain measure. On the basis of all these studies we can, today, attempt to formulate a rather general conception about the chromosphere. In this study an attempt is made to develop such an idea on the basis of differing conceptions concerning the energy balance in the chromosphere. In 1948, Bierman [1] and Schwarzschild [2] put forth the proposal that the kinetic energy of granulation penetrates by some method (let us say in the form of sound waves) to the corona and heats the latter to a high degree. It appears that a tremendous amount of energy is related to granulation, and even a small portion of it is capable of causing radiation losses of the chromosphere and the corona. Schatzman [3] pointed out that when the granules rise there should be a corresponding turbulence which, in turn, causes compression waves that rapidly are converted into shock waves as they are propagated upward. On the basis of the theory of dissipation of shock waves developed by Brinkley and Kirkwood [4], they made some computations on the dissipation of shock waves, and it was shown, in particular, that in the lower corona the shock waves should be completely dissipated since the length of the free path is comparable there with the length of the wave (distance between fronts). On the other hand, the thermal conductivity of the corona is so great that the stationary condition is established at a very low temperature gradient above this layer where the liberation of energy is greatest. In 1955 Unno and Kawabata [5] made a detailed study of the process of the formation of compression waves -- acoustic noises capable of heating the chromosphere and corona. They used the theory of aerodynamic generation of sound waves (noises) developed by Proudman [6] and Lighthill [7], and of a model of the convective zone proposed by Vitense [8]. They concluded that the flow of energy upward amounts to approximately $10^4 - 10^5$ erg/cm^2 · sec., and that this flux was proportional to the 8th order of the accepted value of turbulence velocity so that when the latter is increased by 1.5 it will increase the value of flux by a factor of 25. The turbulent velocity is accepted in [5] as equal to 8% of the convection velocity which, possibly, is underestimated by a few percentile points (cf [9]), and a value 11% of the velocity of convection will give a flux that is 10-15 times greater.

In 1956 Piddington [10] noted that the passage of sound waves in a highly conductive medium in the presence of a magnetic field should propagate magnetohydrodynamic waves whose dissipation may explain the heating of the chromosphere.

Piddington gave a formula for determining the dissipation of magnetohydrodynamic waves due to so-called frictional losses.

In recent years, the idea has often been expressed that hot and cold regions [11-14] should co-exist in the chromosphere. Not too long ago Athay and Menzel [15] constructed a model of such a dual temperature chromosphere on the basis of materials obtained in observations during the 1952 eclipse. Athay and Thomas [16] theoretically demonstrated the necessity for the existence of regions with different temperatures, and that up to a certain height regions with a low temperature ($6,300^{\circ}$) predominated, while regions with a high temperature ($19,000^{\circ}$) prevailed at the higher altitude.

Inside each region the temperature changes little with altitude. The establishment of one temperature or another is determined by the balance between the energy given off and the cooling mechanisms; the temperature jump is associated with the transition from cooling due to the radiation of hydrogen to cooling by the luminescence of helium, which is effective only at another temperature.

Shklovskiy and Kononovich [17], in trying to tie-in the data obtained from optical observations with observations in radio bands given in [18], demonstrated that the values for the temperature should be decreased to $6,000^{\circ}$ and $12,000^{\circ}$ respectively. We considered the possibility of the formation of regions with varying temperatures due to acoustic waves for a purely hydrogen atmosphere.

The study is based on the following considerations. In the convective zone of the sun under the photosphere a portion of the energy of the directed movement of convective elements is converted into the energy of non directional turbulent movement. In the turbulently moving medium chaotically scattered condensations and rarefactions appear continuously. The appearance of the latter is accompanied by the formation of condensation waves which, because of the chaotic nature of the turbulent movements themselves, are of a disorderly character, forming acoustic noise. These waves pass through the photosphere and are virtually not absorbed within it. The speed of magnetohydrodynamic waves in the regions where compression waves are formed is, apparently, considerably less than the speed of sound, so that the removal of energy from the zone of turbulence connected with convection should occur, in the main, because of sound waves. In measure as they are propagated upward the waves become shock waves and explosions occur within them [21]. The speed of magnetohydrodynamic waves increases with altitude considerably more rapidly than the velocity of sound waves, and at a certain height becomes comparable. In the chromosphere absorption of waves increases, and a portion of the energy flux transferred by the waves is converted into heat. One of the problems of this study consists in ascertaining how the greatest amount of heat is given off: in the dissipation of sound waves due to viscosity and due to the dissipation related to the non-adiabatic condensation of a gas on the passage of shock waves of low intensity, or in the dissipation of magnetohydrodynamic waves which upon the propagation of compression waves. The liberation of energy due to Joule heat is very small; we considered the losses of magnetohydrodynamic waves associated with collisions of ions and neutral atoms. These losses are greatest in those places where gas ionization is very low.

Chromospheric heating associated with the passage of waves is compared with its cooling due to radiation. The problem consists in finding out whether there is given off in the dissipation of waves in the chromosphere such a quantity of energy which would be sufficient to cover the expenditure of energy for radiation. It is assumed that the energy flux is uninterrupted in time, and at each moment of time it is in balance with the radiation. In order to find a reply to this problem it is essential, first of all, to determine what kind of radiation brings about a cooling of certain layers of the chromosphere. Basically, the computations in this study pertain to the lower chromosphere.

Each sector of the chromosphere is in a field of radiation traveling from the top downward. In the case of those frequencies whose optical thickness is very great the amount of energy absorbed in a certain volume should be equal to the amount of radiated energy. For example, radiation in the lines of the Lyman series should not extend outside the lower chromosphere because the absorption cross section for these lines is of the order of 10^{-15} cm^2, and even at heights where the concentration of non-ionized atoms of hydrogen constitutes 10^{10} cm^{-3} the optical thickness attains unity at a distance of 1 km. The L radiation flux which emerges from the chromosphere cools the higher layers of the chromosphere principally. In the lower chromosphere, the cooling agent can only be the Bal'merovskoye radiation for which, beginning with a certain rather low altitude, the chromosphere is virtually transparent. We will show, for example, that the chromosphere is transparent in the center of the line H_α at a height of only 1,000 km. For that it is sufficient to use the following formulas (the usual symbols are employed):

$$S_{\nu_0} = \frac{\sqrt{\pi} l^2}{m_e c^2} \frac{\lambda^2}{\Delta\lambda_D} f_{ik}; \quad \Delta\lambda_D = \lambda \sqrt{\frac{2kT}{m}} \quad \text{and} \quad \tau = S_{\nu_0} \int N_2 dl.$$

We will assume that the temperature in the lower layers of the chromosphere is equal approximately to 6,000° and that the number of atoms of hydrogen on the second level can be computed from Boltsman's formula (optical thickness in L_α is quite large, hence such an assumption is quite acceptable). Then, $N_2 = 3 \cdot 10^{-9} N_0$ and S_{ν_0} $(H_\alpha) 6{,}000° = 6 \cdot 10^{-13}$. From the data on the density in the chromosphere given in [25] it can be estimated that in a column with a cross section of 1 cm^2 at a level of 1,000 km there are less than $4 \cdot 10^{20}$ atoms of hydrogen in the chromosphere so that

$$\tau_{1000\,\text{км}} (H_\alpha) = 3 \cdot 10^{-9} \cdot 6 \cdot 10^{-13} \int\limits_{1000\,\text{км}}^{\infty} N_0 dl < 1{,}8 \cdot 10^{-21} \cdot 4 \cdot 10^{20} < 1,$$

from which it follows that above 1,000 km the chromosphere can be considered transparent for a radiation in H*.

We have accepted the fact that a sufficiently good idea of the cooling of the chromosphere layers is given by the radiation in the H_α line. This is, of course, the first approximation, but data obtained from observations enable us to make some corrections where required**.

To construct a general picture of the chromosphere there is no need immediately to use precise values for the density at given heights. It is important to have a proper curve of dependence of the degree of ionization, kinetic temperature, and the like to the density, and the approximate relationship of density to height. The theory of the chromosphere should subsequently explain the value of the density gradient and its change as a function of height and time. Hence, in the following we shall make a study of the relationship of the different processes to density and not to the height in the chromosphere.

By simple considerations it can be demonstrated that in order to compute the ionization and population of the lower levels of hydrogen atoms we can use the formula of Sakh and Boltsman. The fact is that according to practically all models the temperature in the lower chromosphere is of the order of 6,000°, and the boundary temperature of the sun is 4,500°, and since for the ionizing radiation (continuum beyond the limit of the Lyman series) and for the first lines of the Lyman series which produce an excitation of atoms, the chromosphere has great optical thickness, the field of radiation is close to the value corresponding to the intensity of radiation of a black body with a temperature of 5,000 - 6,000°. Under these conditions ionization by electronic collision plays an insignificantly small role [19].

* It should be borne in mind that a cooling of the chromosphere is impeded only by the natural absorption of H_α quanta.

** Radiation of the chromosphere in the Ca II lines of the more powerful metallic lines is of the same order of magnitude as radiation in H_α (cf., for example, [27, 33].

Subsequently, we shall need the value for the degree of ionization of hydrogen and its radiation in H_α. According to Sakh's formulas we computed the values

$$y = \frac{n_p}{n_0} \quad \text{and} \quad x = \frac{n_p}{n_p + n_0} \tag{1}$$

(n_p is the number of protons, and n_o is the number of neutral atoms of hydrogen in 1 cc) for various concentrations from $5 \cdot 10^{13}$ to $5 \cdot 10^{8}$ atoms/cm^3 and for temperatures from 4,800 to 7,000°. It was accepted that at these altitudes $n_e = n_p$. The results of the computations are shown in Fig. 1.

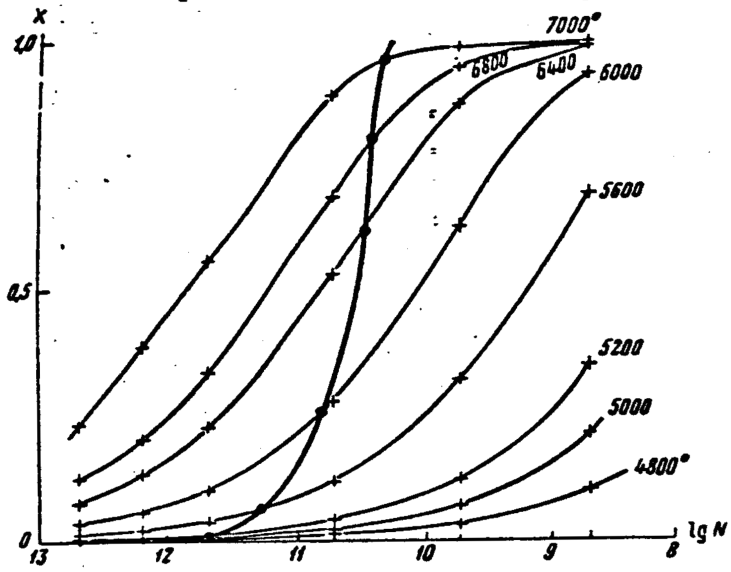

Fig. 1. Ionization of hydrogen at different temperatures and concentrations according to Sakh's formula. The thick line is the assumed curve of ionization in the chromosphere.

From these data we computed the radiation in H_α of 1 gram of hydrogen:

$$E = A_{nn'} n'' h\nu \frac{1}{m_H (y+1)} e^{-\frac{\chi nn'}{kT}}, \tag{2}$$

which, for purposes of convenience was represented as

$$E = \frac{G}{y+1} e^{-B}. \tag{3}$$

It was assumed that the number of atoms on the 3rd level can be computed from the Boltsman formula. The necessary constants were taken from [20]. The computations were made for the same values of density and temperature as above. The results are shown in Table 1.

In order to compare which waves provide the greatest output of energy upon dissipation in the chromosphere, the coefficients of dissipation for magnetohydrodynamic waves and weak shock waves were computed and compared with each other; the coefficient of attenuation due to viscosity was computed also for the compression waves. The energy flux in waves in [5] was taken as being equal to $F = 10^4$ erg/cm^2 · sec. This value can be obtained if we use as our basis the corona heat radiation data [2] and the assumption that all this energy is originally delivered by compression waves (acoustic noises). Taking into account, however, the fact that the energy flux, as we will see subsequently, weakens considerably in the chromosphere we accepted the value $F = 5 \cdot 10^4$ erg/cm^2 sec. According to the independently made computations by Schatzman [3] and Unno and Kawabata [5] it was accepted that the wave frequency $\omega = 0.6$ sec^{-1}.

Piddington's formula [10] was used to obtain the coefficient of attenuation of magnetohydrodynamic waves

$$K_{\text{мг}} = \frac{\omega^2 \tau_n z}{2 V_H S (1+z)^{1/2}},$$

$$\text{where} \quad S \approx 1; \omega = 0{,}6\ сек^{-1};\ z = \frac{1}{y} = \frac{n_0}{n_p};\ V_H = \frac{H}{\sqrt{4\pi\rho}}; \tag{4}$$

$$\tau_n = z\tau_i,\ \tau_i = \frac{3}{4}\frac{1}{n\sigma\bar{v}},\ \sigma = 2{,}3 \cdot 10^{-16}\ см^2,$$

сек = sec.
мг = mg [magnetohydrodynamic]

$\bar{v} = \sqrt{3}\, c,\ c = \sqrt{\frac{kT}{\mu m_H}}$ (c is the velocity of sound; due to the prominent part played by fluorescence sound is assumed to be isothermic), $\rho = Nm_H$, while $\mu = \frac{1}{1 + x}$. The usual symbols are used, H is taken as being about equal to 20 gs. Finally, taking into account (1), we have

$$K_{\text{мг}} = \frac{1-x}{(1+x)^{1/2}} \frac{1}{x^{3/4}} \frac{D}{\rho^{1/2} T^{1/4}};\ D = 1{,}3 \cdot 10^{-14}, \tag{5}$$

and the dissipation of energy per gram

$$E_{\text{мг}} = \frac{1-x}{(1+x)^{3/2}} \frac{1}{x^{3/4}} \frac{DF}{\rho^{3/2} T^{1/4}}, \tag{6}$$

Table 1

E, erg/g · sec

T	N				
	$5\cdot10^{12}$	$5\cdot10^{11}$	$5\cdot10^{10}$	$5\cdot10^{9}$	$5\cdot10^{8}$
4800°	$2{,}23\cdot10^{8}$	$2{,}22\cdot10^{8}$	$2{,}21\cdot10^{8}$	$2{,}15\cdot10^{8}$	$2{,}00\cdot10^{8}$
5000	$7{,}35\cdot10^{8}$	$7{,}34\cdot10^{8}$	$7{,}20\cdot10^{8}$	$6{,}85\cdot10^{8}$	$5{,}84\cdot10^{8}$
5200	$2{,}00\cdot10^{9}$	$1{,}98\cdot10^{9}$	$1{,}92\cdot10^{9}$	$1{,}75\cdot10^{9}$	$1{,}31\cdot10^{9}$
5400	$5{,}40\cdot10^{9}$	$5{,}30\cdot10^{9}$	$5{,}01\cdot10^{9}$	$4{,}20\cdot10^{9}$	$2{,}58\cdot10^{9}$
5600	$1{,}32\cdot10^{10}$	$1{,}29\cdot10^{10}$	$1{,}17\cdot10^{10}$	$8{,}93\cdot10^{9}$	$3{,}96\cdot10^{9}$
5800	$3{,}32\cdot10^{10}$	$3{,}06\cdot10^{10}$	$2{,}62\cdot10^{10}$	$1{,}65\cdot10^{10}$	$6{,}10\cdot10^{9}$
6000	$7{,}06\cdot10^{10}$	$6{,}56\cdot10^{10}$	$5{,}20\cdot10^{10}$	$2{,}59\cdot10^{10}$	$5{,}41\cdot10^{9}$
6200	$1{,}40\cdot10^{11}$	$1{,}24\cdot10^{11}$	$8{,}54\cdot10^{10}$	$3{,}02\cdot10^{10}$	$4{,}57\cdot10^{9}$
6400	$2{,}74\cdot10^{11}$	$2{,}30\cdot10^{11}$	$1{,}36\cdot10^{11}$	$3{,}57\cdot10^{10}$	$4{,}46\cdot10^{9}$
6600	$5{,}26\cdot10^{11}$	$3{,}97\cdot10^{11}$	$1{,}76\cdot10^{11}$	$3{,}17\cdot10^{10}$	$3{,}59\cdot10^{9}$
6800	$8{,}98\cdot10^{11}$	$6{,}06\cdot10^{11}$	$2{,}23\cdot10^{11}$	$3{,}03\cdot10^{10}$	$3{,}35\cdot10^{9}$
7000	$1{,}53\cdot10^{12}$	$8{,}92\cdot10^{11}$	$2{,}30\cdot10^{11}$	$2{,}86\cdot10^{10}$	$2{,}92\cdot10^{9}$

in which F is the energy flux in the waves, and ρ is the density of the substance.

The attenuation of sound waves due to viscosity can be computed using the coefficient K_{vyaz} [21]:

$$K_{вяз} \approx \frac{\omega^2}{\rho c^3}\eta, \qquad вяз = \text{vyaz [viscosity]} \tag{7}$$

in which η is the dynamic coefficient of viscosity. Since $\eta = \frac{1}{3}\sum n_i m_i \bar{v}_i \lambda_i$, in which λ_i is the mean length of the free path of the i-particle and equal for collisions with neutral atoms to $\frac{10^{16}}{N}$ (N is the total number of particles in 1 cm^3) and for collision of ions $\lambda_i = \frac{10^{13}}{N}$, then

$$\eta = \frac{1}{\sqrt{3}} c\rho\left(\frac{(1-x)\,10^{16}}{N} + \frac{x\cdot10^{13}}{N}\right). \tag{8}$$

The smallest possible value of $\eta = \frac{c}{\sqrt{3}}\frac{\rho}{N}10^{13}$ which corresponds to x = 1, i.e., complete ionization. In the lower chromosphere, where in (8) we can disregard the second member of the equation, we have, in accordance with (7):

$$K_{вяз} = \frac{1-x}{1+x}\frac{G}{\rho T}; \; G = 5{,}3\cdot10^{-17}, \tag{9}$$

$$E_{вяз} = \frac{1-x}{1+x}\frac{GF}{\rho^2 T}. \tag{10}$$

The expression for the coefficient of attenuation for weak shock waves can readily be obtained from the formula for the entropy jump on the front of a weak shock wave [30]. The entropy jump on the passage of a shock wave front in computing for one gram of substance, is equal to:

$$\Delta S = \frac{1}{12}\frac{1}{T}\left(\frac{\partial^2 V}{\partial p_1^2}\right)_S (p_1 - p_2)^3. \tag{11}$$

Along with Poisson's adiabatic coefficient pV^{γ} = constant, $V = \frac{1}{\rho}$, which gives the heating up upon the passage of a weak shock wave associated with a front

$$h = T\Delta S = -\frac{1}{12}\frac{\gamma+1}{\gamma^2}\frac{V\Delta p^3}{p^2} = -\frac{1}{12}\frac{(\gamma+1)\gamma p \Delta V^3}{V^3} \tag{12}$$

For 1 cm of path by the wave $dW = \rho h$, in which W is the total energy in the shock wave. The coefficient of absorption is the value K from the relationship

$$K = -\frac{dW}{W} = -\frac{\rho h}{W} = -\frac{dF}{F}. \tag{13}$$

We assume that

$$W_0 = \rho_0 u^2 U t_0 = F_0 t_0, \tag{14}$$

in which U is the front velocity, u is the velocity of the particle behind the front, and t_0 is the time interval characterizing the slope of the front (fig. 6).

It is assumed that t_0 characterizes the quasi-period of the wave: $Ut_0 = \lambda$. Taking into account that $\frac{p}{\rho} = \frac{c^2}{\gamma}$, in which c is the velocity of sound, we have

$$h = \frac{\gamma+1}{12}\frac{c^2 \Delta V^3}{V^3}. \tag{15}$$

From the condition $\rho(U - u) = \rho_0 U$ we compute $\Delta V/V$, and finally, substituting (12) and (14) in (13) we get $K_{уд} = \frac{\gamma+1}{12}\frac{u}{c^2 t_0}$, which with $t_0 = 10$ and $\gamma = 5/3$ we get the expression

$$K_{уд} = \frac{1}{45}\frac{u}{c^3} = \frac{1}{45}\frac{F^{1/2}}{c^{7/2}\rho^{1/2}} \tag{16}$$

уд = ud [dissipation]

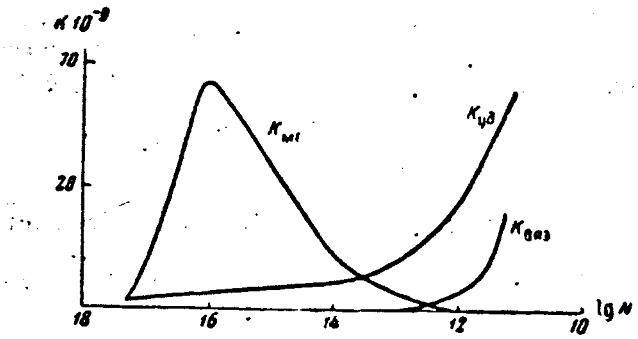

Fig. 2. Comparison of coefficients of dissipation.

in which u is the velocity of movement of the substance in the wave N U = c. A similar expression is used in [3]. We can write

$$K_{\text{уд}} = \frac{1}{(1+x)^{3/4}} \frac{MF^{1/2}}{\rho^{1/2} T^{3/4}} = \mathfrak{M} F^{1/2}, \tag{17}$$

whence

$$E_{\text{уд}} = \frac{1}{(1+x)^{3/4}} \frac{MF^{3/2}}{\rho^{3/2} T^{3/4}}. \tag{18}$$

Energy flux changes with altitude as

$$F = \left(\sqrt{F_0} - \frac{\mathfrak{M} h}{2}\right)^2 \tag{19}$$

The values E_{mg}, E_{vyaz}, and E_{ud} can be presented in a convenient form for computation as ($F = 5 \cdot 10^4$ erg/cm^2 sec):

$$E_{\text{мг}} = \frac{1-x}{x^{3/4}} \frac{2{,}82 \cdot 10^{26}}{T^{1/2} N^{3/2}} \left[\frac{1}{1+x}\right]^{1/2}; \tag{20}$$

$$E_{\text{вяз}} = \frac{1-x}{1+x} \frac{9{,}4 \cdot 10^{35}}{TN^2}; \tag{21}$$

$$E_{\text{уд}} = \frac{5{,}5 \cdot 10^{31}}{T^{3/4} N^{3/2}} \left[\frac{1}{1+x}\right]^{3/4}. \tag{22}$$

The values of E computed by these formulas for different densities and temperatures are given in Table 2.

In order to compare the significance of the various mechanisms of dissipation of energy the coefficients K_{mg}, K_{vyaz}, and K_{ud} were computed on the assumption that $F = 10^4$ erg/cm^2 sec (Fig. 2) for various values of N, a temperature of $T = 6{,}000^\circ$, and an ionization determined from Fig. 1. From Fig. 2 it is apparent that the dissipation of magnetohydrodynamic waves could have played an important part only at the very base of the chromosphere; however, due to the great density there, the output of energy per gram and, therefore, the amount of heating are very small. Let us assume that the hydrogen remains almost entirely non-ionized up to a considerable height; there is no doubt about that. In addition, we should bear in mind that the value of K_{mg} is quite high according to Piddington's formula; V. Ye. Stepanov [22] pointed to this. If, in addition to the values of K, the output of energy depends also on the relationship of the velocities of the shock and magneto-hydrodynamic waves the output of energy in the lower part of the chromosphere E_{mg} is still less than E_{ud} because $V_{H/C}$ is small.

Table 2

E_{ud} erg/g · sec

T	N				
	$5 \cdot 10^{12}$	$5 \cdot 10^{11}$	$5 \cdot 10^{10}$	$5 \cdot 10^{9}$	$5 \cdot 10^{8}$
5000°	$1{,}17 \cdot 10^{8}$	$3{,}66 \cdot 10^{9}$	$1{,}14 \cdot 10^{11}$	$3{,}40 \cdot 10^{12}$	$9{,}31 \cdot 10^{13}$
6000	$8{,}97 \cdot 10^{7}$	$2{,}61 \cdot 10^{9}$	$6{,}77 \cdot 10^{10}$	$1{,}58 \cdot 10^{12}$	$4{,}09 \cdot 10^{13}$
7000	$5{,}94 \cdot 10^{7}$	$1{,}41 \cdot 10^{9}$	$3{,}48 \cdot 10^{10}$	$1{,}03 \cdot 10^{12}$	$3{,}29 \cdot 10^{13}$

E_{mg} erg/g · sec

T	N				
	$5 \cdot 10^{12}$	$5 \cdot 10^{11}$	$5 \cdot 10^{10}$	$5 \cdot 10^{9}$	$5 \cdot 10^{8}$
5000°	$3{,}38 \cdot 10^{7}$	$4{,}46 \cdot 10^{8}$	$5{,}85 \cdot 10^{9}$	$7{,}40 \cdot 10^{10}$	$8{,}35 \cdot 10^{11}$
6000	$4{,}02 \cdot 10^{6}$	$4{,}95 \cdot 10^{7}$	$5{,}30 \cdot 10^{8}$	$4{,}02 \cdot 10^{9}$	$1{,}84 \cdot 10^{10}$
7000	$6{,}50 \cdot 10^{5}$	$5{,}45 \cdot 10^{6}$	$2{,}84 \cdot 10^{7}$	$2{,}80 \cdot 10^{8}$	$2{,}18 \cdot 10^{8}$

E_{vyaz} erg/g · sec

T	N				
	$5 \cdot 10^{12}$	$5 \cdot 10^{11}$	$5 \cdot 10^{10}$	$5 \cdot 10^{9}$	$5 \cdot 10^{8}$
5000°	$7{,}50 \cdot 10^{6}$	$7{,}45 \cdot 10^{8}$	$7{,}20 \cdot 10^{10}$	$6{,}50 \cdot 10^{12}$	$4{,}88 \cdot 10^{13}$
6000	$5{,}90 \cdot 10^{6}$	$5{,}10 \cdot 10^{8}$	$3{,}47 \cdot 10^{10}$	$1{,}35 \cdot 10^{12}$	$2{,}38 \cdot 10^{13}$
7000	$3{,}38 \cdot 10^{6}$	$1{,}56 \cdot 10^{8}$	$3{,}30 \cdot 10^{9}$	$5{,}45 \cdot 10^{10}$	$2{,}68 \cdot 10^{11}$

In the chromosphere K_{ud} and K_{vyaz} are of the order of 10^{-8} cm^{-1}; this means that along the length of the chromosphere the energy flux changes only several fold, i.e., that the formulas (6), (10), and (18) can be applied.

The balance of energy in the chromosphere should be ensured by the equality of energy given off in the dissipation of the E waves, and the energy carried off by radiation - $\mathcal{E}$.

In Fig. 3 we have shown the relationship of the radiation in H to the value N- the concentration of atoms and ions of hydrogen in 1 cm^3 for various possible values of temperature, as well as the relationship to those same parameters for the quantity of energy given off in the dissipation of shock waves. The curve E virtually does not change with temperature, but for each value N it intersects with the curve for $\mathcal{E}$, which corresponds to a certain temperature.

From the graph of Fig. 3 we can determine at what temperature at a given height (at a given density) we can have a balance of energy at the accepted assumptions. It is apparent on this graph that, beginning at a certain height, at no value of temperature is the radiation of hydrogen such as to ensure the balance between the energy given off and carried away. According to [16] this means that at a given energy flux the luminescence of hydrogen cannot ensure the balance and that here there must be a temperature jump to such a value at which there comes into being some other cooling mechanism, e.g., the luminescence of ionized helium (temperature of the order of 12,000 - 19,000° K). At a practically unchanging energy flux, beginning at a certain height, the temperature in the chromosphere should increase markedly. This may be expressed as follows in another way: above a certain level in the chromosphere there should prevail "hot regions", and below that -- cold regions.

It should be mentioned that even in the hot regions the optical thickness in the lines of the Lyman series remains high to a certain altitude [23]. With the aid of the graph in Fig. 3 we can describe for the lower part of the chromosphere the relationship between the concentration of atoms of hydrogen and the temperature. This relationship is shown in Fig. 4. The data from Fig. 4 can

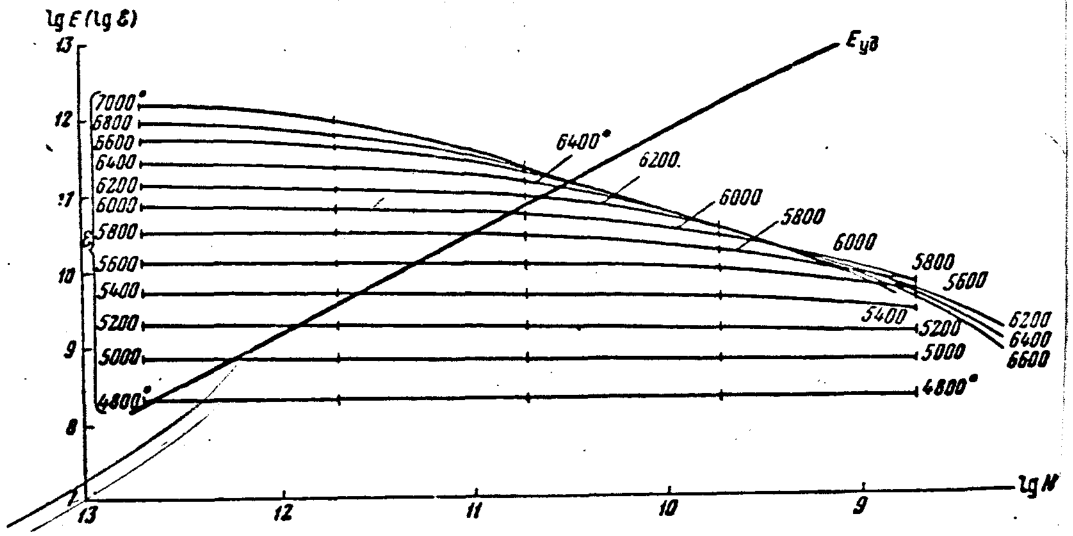

Fig. 3. Comparison of energy carried off by the radiation of hydrogen in H_α (curves $\mathcal{E}$) and the dissipation of energy of shock waves (curve E).

be used so that with the aid of Fig. 1 we can find the relationship of the degree of ionization of hydrogen x to the concentration. This relationship is shown in Fig. 1 by a heavy line. It is apparent that the ionization-density curve is quite sharp. The result obtained agrees well with the result obtained by Wooley and Allen [24] who also got a steep ionization curve, the half ionization being attained at the same value and temperature as was true in our case.

We might try to explain the existence of hot regions below the level where this transition is tied in with the regular decrease in density with height. The wave pileup and the fluctuation of energy flow may result in an increase in the energy flux in certain regions. Assuming that at a given level the gas pressure is a fixed quantity we should further assume that the value N will become inversely proportional to T because $p = (1 + x)\,NkT$. From this, using formula (22) we find that the liberation of energy will be proportional to $T^{\frac{1}{4}}$. This means that if, at this density the temperature that is increased at random reaches an indicated critical value, then the increase in temperature will continue until a new cooling mechanism is triggered into action which would insure a sufficiently effective withdrawal of heat. In other words, as soon as such a temperature value, at a given density, will be attained in which the radiation will be a function of the temperature in an order less than $\frac{1}{4}$, the temperature jump should occur at a level lower than is required by the decrease in density with the height for a uniform case. The random increase in energy flux in any region may be very considerable. The decrease in flux will result in the formation of a cold region again. Of course, a change in the flux or the random

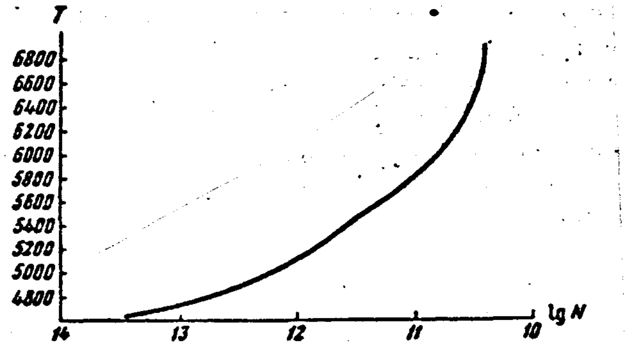

Fig. 4. Relationship of temperature to concentration of hydrogen in the cold regions of the lower chromosphere.

change in temperature may result in the formation of a hot region only if these changes are so marked that they cannot be compensated for by changes in radiation of hydrogen. The hot regions, therefore, are dynamic formations whose life period is not very great*.

We can also explain the lowering in the observed chromosphere above the spots, as noted also by Mustel' [11] and Krat [31]. Actually, if in the region of the magnetic field the total pressure, equal to the sum of the magnetic $H^2/8\pi$ and gas $(1 + x)$ NkT pressures, should be balanced by the gas pressure from without and the temperature in the region of the magnetic field (e.g., above the spot) and within it are the same, balancing is possible only when the density in the region with the magnetic field is less than in the neighboring regions. But a decrease in density, as was shown in the above, results in an increase of energy yield and, consequently, in the formation of a hot region

* The formation of a hot or cold region may be tied in with the fluctuation in the density at a given height.

at a comparatively low altitude. Later, we propose to compute the possible contrast between the hot and cold regions which should be observed in H_α and compare it with the observed contrast between the dark and light components of the chromospheric grid of the unperturbed region of the solar disc. The question of reflecting acoustic waves in the chromosphere was studied in [3]. We can say that acoustic waves are reflected only at the boundary of the temperature jump region. In the case under consideration the flux changes only by a factor of two without changing the order of magnitude because, according to Shatsman, the energy flux becomes inversely proportional to the square of the velocity of sound, i.e., it changes proportionately with the temperature. In the case of magnetohydrodynamic waves the reflection in the chromosphere is not considerable [10].

In the very lowest portion of the chromosphere the temperature, apparently, is under $5,000^{\circ}$. The energy radiated in these regions may be given off with the dissipation of magnetohydrodynamic waves and is brought in because of thermal conductivity. The steady radiation given off from these layers is a result mainly of the formation of negative hydrogen ions. It should be borne in mind that luminescence in the continuous spectrum can be explained in part by the simple scattering of photospheric radiation, i.e., that not all of the radiation emerging from these layers results in cooling them.

For the upper, hot, and completely ionized layers of the chromosphere, the comparison of E_{ud} with computations for the luminescence of ionized helium made in [16] shows that a considerable amount of energy is given off on account of compression waves.

We can make a rough estimate as to height in sound waves that breaks occur and at what height these breaks are so great that they cannot be deemed weak.

In the upper portion of Fig. 7 there is shown a profile of a sound wave. The point B moves in a fixed system of coordinates with the speed of sound wave c, and point A moves with the speed of u + c. The velocity of point A relative to point B is equal to u. We can figure approximately that the break occurs when there is brought about a situation of an image in the lower portion of the figure, i.e., when the point A will move relative to the Point B a distance equal to $\lambda/4$. During this time that is equal, say, to t, the wave will move a distance L. Thus,

$$t = \frac{L}{c} = \frac{\lambda/4}{u}; \quad \lambda = ct_0; \quad u = \sqrt{\frac{F}{\rho c}}.$$

Consequently,

$$L = \frac{t_0 c^{3/2} \rho^{1/2}}{4F^{1/2}} = 2{,}5 \frac{k^{3/4} T^{3/4}}{F^{1/2} m_H^{1/4}} N^{1/2}.$$

Assuming that $T = 5 \cdot 10^3$ and $F = 5 \cdot 10^4$, we get $L \approx 5N^{\frac{1}{2}}$. Thus, in the very lower portions of the chromosphere where $N = 10^{14}$, $L \approx 5 \cdot 10^7$, i.e., over a distance of only 500 km of travel, the sound wave changes over into a shock wave.

The formulas for a shock wave of weak intensity cannot be used if $u > c$. If u/c is several times greater than unity the shock wave should be regarded as being powerful; as we know, it attenuates more strongly than a shock wave of low intensity.

The value $u = c$ is attained with a density of ρ determined from the relationship $\frac{u}{c} = \left(\frac{F}{\rho c^3}\right)^{1/2} = 1$, i.e., when

$$\rho \sim \frac{F}{c^3} \quad \text{and} \quad N = \frac{5 \cdot 10^4 m^{1/2}}{k^{3/2} T^{3/2}}.$$

For the higher layers of the chromosphere $T \approx 2 \cdot 10^4$ so that the explosion is greater at $N \approx 10^{10}$, i.e., higher than the temperature jump.

Since at altitudes where $N = 10^{10}$ the density in the chromosphere changes very slowly with the altitude, then u should be several times greater than c at a rather considerable altitude. Hence, the consideration held in this study may be correct also for higher altitudes. It is possible that the magnetic field also delays the formation of powerful explosions.

Let us analyze the relationship of density to altitude. In the case of layers with a fixed temperature the gradients of density should be for a case of T = 5,000° and a non-ionized medium (the lower chromosphere)

$$\beta_1 = \frac{\mu g}{RT} = \frac{g}{RT(1+x)} \approx 6{,}56 \cdot 10^{-8}, \tag{23}$$

and for a case where T = 19,000° and total ionization $\beta_2 = 0.87 \cdot 10^{-8} cm^{-1}$.

In connection with the fact that with increased altitude there is an increase in the relative number of hot regions, there should be observed a smooth transition of the β density gradient value from larger to smaller values. Shown in Fig. 5 is the observed curve of density according to data provided by Van de Holst [25] and straight lines drawn with slopes of $6.56 \cdot 10^{-8}$ and $0.57 \cdot 10^{-8}$. For the cold regions of the chromosphere the relationship of density to altitude (the broken line in Fig. 5) is drawn with the aid of Fig. 4 and the numerical integration of the equation for hydrostatic equilibrium:

$$h_2 - h_1 = \frac{R}{g}(1+x)\int_{N_1}^{N_2} \frac{T(N)}{N}\,dN. \tag{24}$$

Taken as the initial point is the value $N = 10^{13.4}$ at an altitude of h = 1,000 km [25]. As one might expect, this relationship falls short of the observed curve, a fact related, as previously indicated, to an increase in the relative number of hot regions with height.

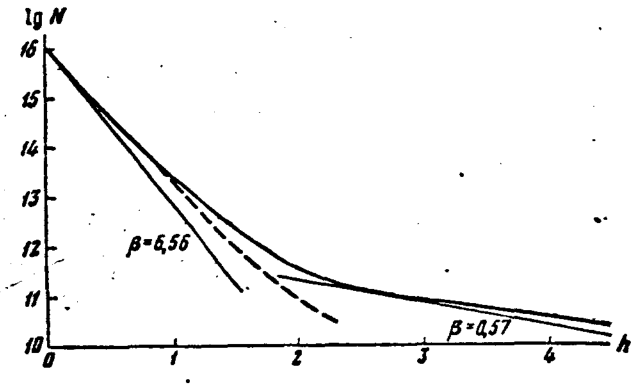

Fig. 5. Relationships of density to height in the chromosphere.

Solid line -- from data by Van de Holst [25]; broken line -- according to computations made in the present study for cold regions of the chromosphere. Straight lines drawn with slope corresponding to β = 6.56 and 0.57.

It is necessary also to take into account the possible support of the chromosphere due to sound waves.

The equation for hydrostatic equilibrium in this case is as follows:

$$dp + d(\rho u^2) = \rho g\,dh, \tag{25}$$

in which $u = \left(\frac{F}{\rho c}\right)^{1/2}$ is the velocity of matter in sound waves. Spectroscopically, this value is manifested just like turbulent velocity: it extends the line. The question of turbulence in the chromosphere was investigated by A. B. Severnyy [28], and by Unno and Kawabata [5] with respect to sound waves. It should be mentioned that the turbulent velocity that we observed is spectroscopically not equal to u (if u is the velocity of matter on the immediate wave front) but that it is an median value averaged out for time and for directions, i.e., it should be several times smaller than u [3]. The value u increases markedly with altitude due to the drop in the density ρ and it reaches 10^6 cm/sec.

Fig. 6. Shape of shock wave; t_0 = time interval between passage of fronts.

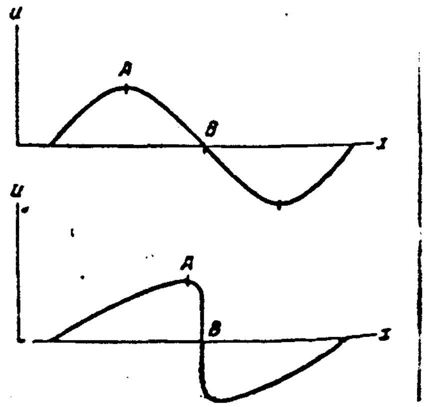

Fig. 7. Conversion of sound wave to shock wave.

The second member of the right-hand side of equation (25) can be represented as

$$d\left(\frac{F}{c}\right) = \frac{c\,dF - F\,dc}{c^2}. \tag{26}$$

Whence

$$\frac{dp}{dh} + \frac{1}{c}\frac{dF}{dh} - \frac{F}{c^2}\frac{dc}{dh} = \rho g. \tag{27}$$

Let us compare the individual members of the left portion of this equation:

$$\frac{F}{c^2}\frac{dc}{dh} \approx \frac{5\cdot 10^4\cdot 10^4}{10^{12}\ 10^8} \sim 5\cdot 10^{-12}, \quad \frac{1}{c}\frac{dF}{dh} = \frac{K}{c} = \frac{10^{-8}}{10^6} \sim 10^{-14},$$

$$\text{a}\ \frac{dp}{dh} = \frac{2kTdN}{dh} = 2kTN\beta.$$

i.e., everywhere in the lower chromosphere $dp/dh > 10^{-10}$. Consequently, attenuation of sound waves in the lower chromosphere does not bring about any noticeable changes in the density gradient. In the upper part of the chromosphere support by sound waves apparently becomes substantial, especially in the area of temperature jump (member with $\frac{dc}{dh}$).

The question of propagation of shock waves in the presence of a magnetic field and their dissipation in a magnetic field should be considered separately. The estimates made demonstrate, however, that the presence of a magnetic field in a non-perturbed chromosphere will not essentially change the results obtained in this study.

A certain confirmation of the assumptions made in this study can be obtained if we compare the observed output of energy in H_α [27,29] with what should be observed according to our calculations. For example, we found that at an altitude of 1,500 km the value $T \approx 5,200^\circ$ and the radiation in H_α per one gram of matter is (Table 1):

$$\mathcal{E} = 2\cdot 10^9 \quad \text{erg/g} \cdot \text{sec} \tag{28}$$

The absolute photometry of chromospheric lines made by Vyazanitsin [27,29] gives us, for total radiation in H_α at a height of h = 1,500 km, the value $\lg \mathcal{E}(h) =$ $= 15.5$ and a gradient $\beta \cdot 10^{-8}$.

Resolving Abel's equation [26] we will find that the radiation of 1 cm^3 at a height of 1,500 km is:

$$j(h) = \frac{E(h)\beta^{1/2}}{\sqrt{2\pi R_\odot}} \approx 5\cdot 10^{-3} \quad \text{erg/ cm}^3\ \text{sec}$$

which recalculated for 1 gram (concentration of atoms of hydrogen at this height N = 12.0 is determined from Fig. 5) gives us:

$$E \approx 3\cdot 10^9 \quad \text{erg/g} \cdot \text{sec} \tag{29}$$

The value (29) is found to be in fair agreement with the value found in (28).

Summarizing the foregoing and omitting details, we can draw up the following idea concerning the structure of the chromosphere and the reasons for its formation. Let us assume a sun having no convective zone, chromosphere, nor corona. If convection has begun at a certain moment there should inevitably come into being a chromosphere and a corona -- exactly as those actually observed. As a matter of fact, in the upper part of the convective zone turbulent movements will begin as a result of dispersion of convective nuclei; these movements in turn will cause the formation of condensations and rarefactions with the resultant generation of sound waves. In the photospheric layers these waves will not undergo dissipation, and will be propagated upward. Upon ascending the waves are very quickly converted into shock waves. Only in those places where the density is low enough do the waves become dissipated, and the energy given off increases the temperature, which, in turn decreases the density gradient. Warmup and decrease in the density gradient will occur until a temperature and density will be established such that a balance will take place between the energy given off and the energy carried off by radiation. Such a balance is insured at different altitudes by various mechanisms of de-excitation [vysvechivaniye]. In the lower layers this is the fluorescence of hydrogen; higher up it is that of ionized helium; and, finally, in the corona it is the fluorescence of highly ionized atoms of different metals, the recombination fluorescence of hydrogen and ionized helium and the "evaporation" of particles from the corona [32]. The greatest liberation of energy occurs in the corona where, due to the drop in density and increase in temperature, the length of free path of particles becomes comparable to that of a sound wave (the distance between fronts for a shock wave). At this height the compression waves dissipate completely and, at higher layers, the temperature of the corona is maintained only because of thermal conductivity. Thus, the corona is not warmed by the chromosphere, as some authors feel; rather, it is heated directly*. Furthermore, a portion of the energy liberated in the corona is transmitted into the upper chromosphere.

If the ideas set forth are correct, the entire structure of the chromosphere and corona are determined, in the main, by the values of just one parameter, the value of energy flux carried by the sound (shock) waves. The components of the structure are a function, naturally, of the wave frequency, the magnitude of field voltage, etc. The value of energy flux F used here and the values obtained for the chromosphere, are, of course, merely approximations. The data available on the mechanisms of chromospheric cooling, the coefficients of absorptions, the energy flux, etc. can be used in drawing a general idea of the chromosphere, but a model of the chromosphere can be constructed only on the basis of direct observations.

In conclusion, I wish to express my appreciation to Member Correspondent of the Academy of Sciences of the USSR, A. B. Severnyy for his valuable advice in drawing up this manuscript.

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